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NEW CONCEPTS FOR PROVISIONING PARAMETER ESTIMATES. PART I. MAIN--ETC(U)

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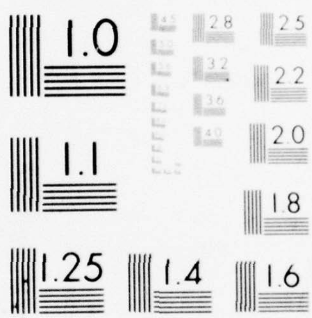

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NEW CONCEPTS FOR PROVISIONING PARAMETER ESTIMATES: PART I: MAINTENANCE FACTORS AND REPLACEMENT RATES

US ARMY
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DRC
INVENTORY
RESEARCH
OFFICE

December 1976

ROOM 800
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2nd and Chestnut Streets
Philadelphia Pa. 19106

NEW CONCEPTS FOR PROVISIONING PARAMETER ESTIMATES: PART I: MAINTENANCE FACTORS & REPLACEMENT RATES

TECHNICAL REPORT

BY

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DECEMBER 1976

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Several promising techniques of initially estimating and subsequently updating maintenance factors (replacement rates) for parts in a new system are presented. This factor is an important parameter in the determination of initial provisioning quantities. Distinctions are made between replacements and failures, and between updating maintenance factors and updating demand estimates.

The retainability concept is introduced wherein analogs of reliability formulae may be used to obtain initial estimates. Use of family rates for groups of parts is discussed also.

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Block 20 - Abstract

Updating schemes utilize variable weighting of past observations, as in Kalman filters.

A summary of current practices is included.

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CHAPTER I

INTRODUCTION

In determining the quantity of a part to be initially provided to a support level (supply and maintenance), there are five or six important provisioning parameters, the values of which have to be initially estimated before deployment of the end item/system and before consumption experience is obtained: maintenance factors, replacement task distributions, maintenance task distributions and condemnation rates for reparables, and turn around times (both supply and repair). In this report and [7], I shall treat the estimation of each parameter for the most part independently, but I should like to indicate in this section how these parameters for a part are inextricably entwined with each other as well as with those of other components, sub- and supra- included. This section should engender caution not futility.

When a part of a system fails sometimes it is replaced; sometimes it is replaced when it does not fail and something else fails; sometimes when nothing fails. The maintenance factor indicates this replacement rate. What percentage of these replacements should be done at organization DSU, GSU and DEPOT support levels? It depends upon the resources (men, parts, test equipment) at each level. But the costing of various resource allocation schemes and subsequent replacement policies depend upon the replacement rates and probabilities of different modes of failure. The frequency of replacement of a part at a given support level also depends upon the frequency with which a reparable next higher assembly is repaired (and may need this part replaced) at this level. In turn this level of repair analysis is also a resource allocation problem, combined with a repair versus throwaway decision; and this problem depends upon failure and replacement probabilities of the parts within the reparable assembly. The level of repair analysis will render prescriptive* maintenance task distributions and condemnation rates - maybe; these values depend upon the MTD's of higher indenture levels.

---

*How things should occur.

Also predictive* MTD's and condemnation rates depend greatly on the surplus or deficit of spares and parts at various levels (if a part is not available, the assembly may be sent to another level), and on human error and caprice. Going full circle on these interactions, one can see that one task distribution may produce higher total replacements (and hence maintenance factor) than another distribution (e.g. 100% maintenance at depot may entail fewer erroneous replacements). The time to repair and to order a necessary part at various support levels also impact on the where to repair and where to replace decisions. Conversely the time to obtain a part from a higher level may be long if the part is not there due to other poor provisioning parameter estimates, and time to repair can be longer due to poor estimates of facility requirements.

Logistics support analysis attempts to cover all these system support problems in an organized manner, but many of the interactions are not or can not be considered. Maintenance support models and simulations are useful tools for evaluating alternatives but suffer the need for a great number of inputs, the values of many (particularly costs) being questionable. And in essence, the task distributions, failure rates, and turn-around times in these simulation models don't account for all the field maintenance problems and over-usage, under-usage and misusage of the end items.

Concentrating on the maintenance factor, we next discuss the status of current practices and reliability handbooks. Then the body of the report (Chapters II, III, IV) will present innovative techniques for initially estimating and updating maintenance factors.

*How things would occur

Summary of Current Practices

DARCOM Headquarters, DRCMM-MP, distributed questionnaires designed by IRO to the six Commodity Commands. Ten respondants from each Command familiar with their current provisioning parameter estimation practices completed the questionnaires. Table 1.1 summarizes the consensus opinions on various aspects of the maintenance factor methodology. Other provisioning parameters reviewed were: washout rates, maintenance task distributions, and repair cycle times; summaries of these responses are presented in another IRO report [7].

In most cases the initial maintenance factor estimates are engineering judgements of provisioners - with and without backup test data. If the estimate is updated at all, it is not part of a formal procedure in most cases. Although it varies by system being provisioned, personnel of the provisioning activity are not utilizing the reliability engineers expertise for adjusting for environment or end item usage. Despite these deficiencies, most respondants felt the initial estimate was adequate or good (probably meaning as good as could be expected under the circumstances). It was felt the estimates were too high, indicating many components are over provisioned.

Handbooks* of Reliability, Failure Rates and Replacement Rates

Two reliability handbooks produced by the Rome Air Development Center [6], [11], - one for electronic components and one for non-electronic components - and the Government-Industry Data Exchange Program (GIDEP) summaries of rates are natural first sources in obtaining initial technical estimates, but are not the last word, in lieu of any ad hoc data for the components in question.

The handbooks give failure rates λ per part per million hours of operation. For practical purposes, 10^6 operation hours is an age value (with some exceptions regarding on-off cycles). λ is assumed constant, i.e. components are operating in a region of random failures; a usage factor is only implicitly considered by the usage variable's relation to time. These assumptions may not be too bad for electronic parts, but for

*General term for comprehensive sources of summary data.

non-electronic, mechanical parts the assumptions are admittedly worse - but the simplest considering the sparsity of data for mechanical components. Note also that mechanical parts are more often specifically designed for a next higher assembly (NHA); the handbook gives general constant λ's which may be inadequate for the specific system in question. Also in the non-electronic case, the NHA or end item may have usage variables that are more important than hours of operation.

Both handbooks present environmental and application factors to adjust a λ given for a base case. The factors for mechanical parts are less developed - only given for several general environments, if at all - but seem to be the best available for general application. It is appropriate to note here that care must be exercised in applying these factors; particularly, injudicious values of "failure factor 3" in the PMDR to adjust maintenance factors for deployment area can negate a perfectly reasonable replacement rate.

GIDEP is a computerized data exchange. Failure and replacement rates are, for the most part, again given per million hours. User rather than vendor data are compiled. Environmental factors are also stored. The caveats mentioned above again apply.

	CONSENSUS OPINIONS	AVSCOM	MICOM	ARMCOM	TACOM	ECOM	TROSCOM	
I	Most utilized method of obtaining initial estimates	6	1	5-6	5	5-6	9	See Code Key in Table 1.2
II	Most utilized method of updating initial estimates	15	15	14	13-14	14	13	
III	Average Quality of initial estimate	Adequate to Good	Adequate to Good	Adequate	Good	Good	Adequate	
IV	Bias of initial estimate	None	High	High	High	High	High	
V	Degree to which usage data is available and adjustments made for end item usage	Little	Good	Varies	None or Little	None	Little	
VI	Amount of coordination with reliability engineers	Seldom	Varies by System	Seldom or Sometimes	Never or Frequent (by system?)	Seldom	Varies, but Mostly none	

TABLE 1.1 CONSENSUS OPINIONS - ASSESSMENT OF CURRENT MAINTENANCE FACTOR METHODOLOGY

TABLE 1.2

Code	Parameter: Maintenance Factor Subject: Initial Estimate/Event
1	Estimate procured from contractor as part of the Provisioning Technical Documentation (MIL-STD 1552) with supporting test data or other empirical data to back up the estimate.
2	Estimate procured from contractor as part of the Provisioning Technical Documentation (MIL-STD 1552) without supporting data to back up the estimate.
3	Estimate procured as described under Event 1 and then modified by technicians of the Army Provisioning Activity.
4	Estimate procured as described under Event 2 and then modified by technicians of the Army Provisioning Activity.
5	Estimate furnished by technicians of the Army Provisioning Activity based on engineering judgement and backed-up by documented test or other empirical data.
6	Estimate furnished as described under Event 5 except without documented back-up data.
7	Estimate derived by technicians of the Army Provisioning Activity through application of the "Objective Determination of Maintenance Factors" procedure specified in (Draft) AMC Pamphlet AMCP 750-5, June '74.
8	Estimate derived by technicians of the Army Provisioning Activity and using handbook type failure data and failure mode-effects and reliability model analysis prescribed in AR 702-3.
9	Estimate derived through application of practices other than those described in Events 1 through 8. (Please provide explanation on reverse side).

TABLE 1.2 (cont)

Code	Parameter: Maintenance Factor Subject: Updating Practices/Event
	(Note: The term "data" used below refers to recorded, quantitative information required to update the initial estimate at the National Maintenance Point level (NMP)).
10	Data is obtained through a sample data collection (SDC) plan (Ref. TM 38-750).
11	Data is obtained through routine feedback of records independent of or supplemental to SDC activities.
12	Formal procedure applicable to local NMP is used to update initial estimate with actual experience data.
13	Initial estimate is update with actual experience data without application of a formal procedure.
14	Data suitable for updating is not obtained.
15	Previous estimates documented in Selection Worksheets or equivalent data files (e.g., PMDR) are periodically revised to reflect updated values.

CHAPTER II

INITIAL ESTIMATES BY SYSTEM RETAINABILITY ANALYSIS

2.1 Replacement Rates vs Failure Rates

A casual investigation of handbooks of failure rates and replacement rates reveals that the latter are often 1.5 to 2 times the value of the former for a given part. On the other hand, as evidenced in the Introduction, those involved in making maintenance factor estimates are concerned with over-estimation of these factors. Clearly a distinction has to be made between the two types of rates as well as a distinction between the field environment (in which actual maintenance factors arise) and the testing environment from which reliability predictions (i.e. failure rates, the basis for many initial maintenance factors) are made.

Whereas failure rates and reliability of a part, assembly, etc. depend on physical characteristics, environment, and system intra-connections, replacements depend upon maintenance or replacement policies - imperfectly carried out - in conjunction with component failure rates. Complicating any analysis, in terms of point of entry, is the potential for circular reasoning, since replacement policies in turn depend on estimated replacement rates.

One should keep in mind that a failure does not always engender a replacement (which is with what one is really concerned in a MF estimate); the part may be adjusted while on the assembly, or the whole assembly may be inefficiently replaced. Conversely, replacements are made when no failure occurs; erroneous detection of the faulty part, scheduled replacements, or standard policies of replacing all instances of a particular part when one fails - are all contributory factors.

In general, obtaining the replacement rate for a component/assembly (CA)* based on its internal structure, its relation to other CA's, and its maintenance environment is an ad hoc procedure. The next two sections will present a methodology, which I term retainability analysis, that gives structure to this procedure.

---

*My generic for part, component, assembly, subsystem.

2.2 Block Retainability Analysis

As with reliability analysis, one obtains the probability of replacement of a block of parts based on internal corrections and replacement probabilities of the individual parts; this block is used in the subsequent analysis of the block diagram of the next higher assembly (NHA). In the next section I will exemplify the procedure, but I do not intend to cover or generalize all possibilities of replacement policies, failure modes, and block diagrams. The example demonstrates an inductive process or block by block buildup, where at a given step one must consider the CA, its block diagram of sub-CA's, and its NHA. I assume if a CA is removed, it is replaced with another while it is being discarded or repaired; if the same CA is returned, I assume this is equivalent conceptually to the case of repair without removal for the purposes of MF determination.

From lower level analyses, one knows the probability of failures, probability of replacements, and number of replacements/year (random and scheduled) for each component C_i of the CA. Conceptually replacement rates and probabilities should be lower than failure rates and probabilities since many failures require only an adjustment rather than replacement of the component C_i. Historically, however, replacement rates are higher (see 2.1). There are three reasons for this (excluding factors that the failure rate estimate may not have considered, such as extreme environment or operator misuse):

Dependencies (C_i fails often if C_j does)
Faulty Diagnoses
Special Policies

Dependencies need not be considered if the reliability engineer has done his job and has given failure rates in terms of compounded, highly dependent components. Faulty diagnoses are quite common and a field technician may replace many workable parts to "get an engine going". Replacing identical or related components when a failure occurs is a common type of special policy.

A determination by component of the maintenance process constraints

is the next important step to ascertain for which failures does CA have to be replaced.

Next component probabilities are adjusted to account for dependencies and faulty detection probabilities.

Based on probabilities and maintenance constraints, one obtains a retainability S_i for each C_i (probability that CA can be retained in NHA). These retainabilities can be combined for series - parallel block diagrams using analogs of reliability formulae to obtain the retainability S_{CA} of the component/assembly.

Finally a necessary simplifying assumption is that S_{CA} is related to the random replacement rate r as reliability R_{CA} is related to failure rate λ, i.e.

$$S_{CA} = e^{-rt} \tag{2.1}$$

where t = 1 year and component probabilities have been computed for one year. Then random replacements per year for one CA in one NHA

$$r = - \ln S_{CA} \tag{2.2}$$

If M = number of CA's in all NHA's of a given type, then the total number of replacements/year

$$\lambda_T = M\,(r + r') \tag{2.3}$$

where r' = scheduled replacement rate.

2.3 Example

See Figure 2.1. This is not a formal procedure, but the basic concept of retainability is exemplified.

Component Probabilities (without regard to any CA special relations)

f_i = probability of failure of component C_i

q_i = probability of replacement of component C_i

In particular in this example, set $f_2 = q_2$

Dependencies

If C_1 fails, C_2 fails with probability $f_{2/1}$

Hence from above, $q_{2/1} = f_{2/1}$

Faulty Diagnoses

If C_7 fails, C_8 is replaced with probability $q_{8/7}$

Special Policies

If one C_6 fails, replace all C_6's

Maintenance Constraints

A. On components/assembly CA

i) If C_1, C_3, C_4, C_5, C_6, C_8 replaced, CA has to be removed (and replaced)

ii) When C_7 replaced, CA removed and replaced with probability 1/2

iii) If C_9(IX) replaced, CA does not have to be

iv) If C_q(VIII) replaced, CA does have to be

B. On sub-components

C_3 is replaced r_3' times a year (non-random)

Procedure

1. Adjust any component probabilities

1.1 $f_1' = f_1 + f_2 - \text{prob } (C_1 \text{ and } C_2 \text{ both fail})$

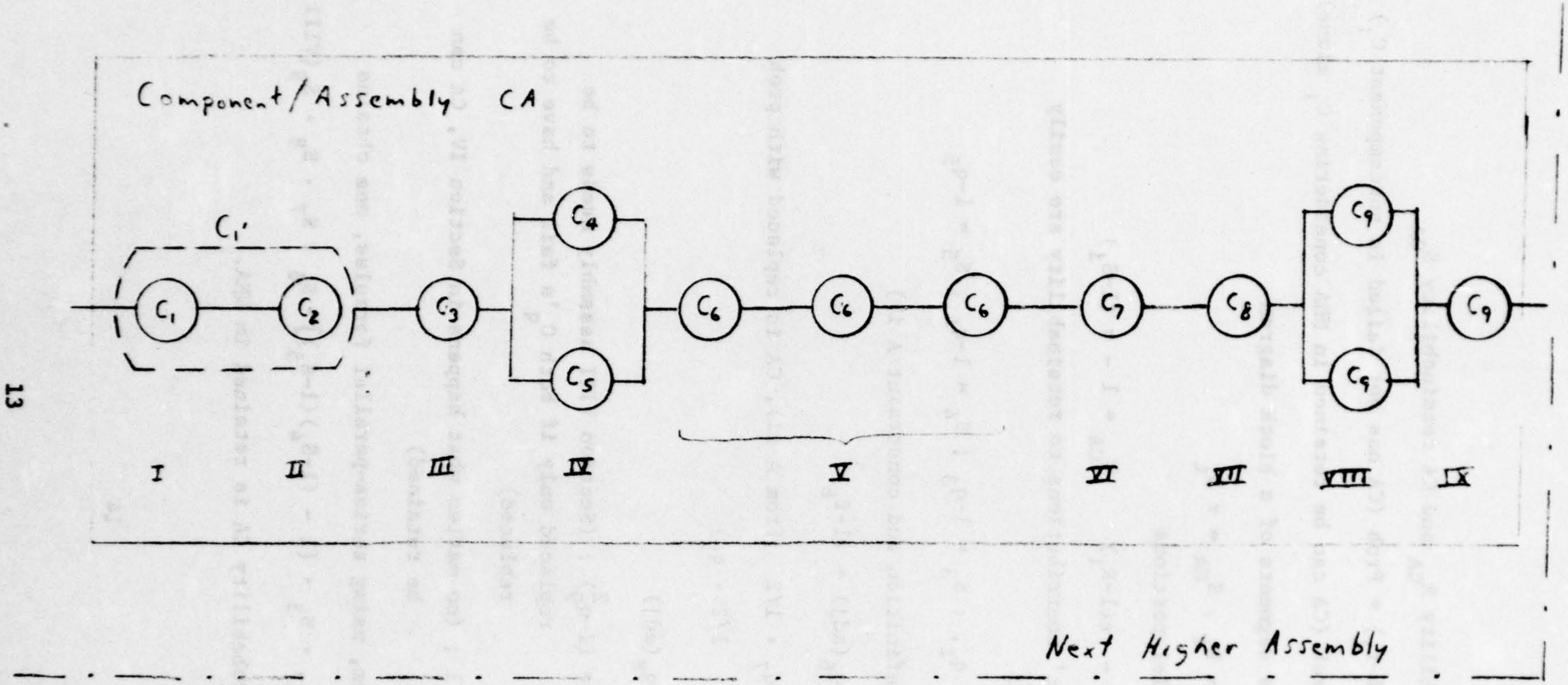
$$= f_1 + f_2 - f_{2/1} \cdot f_1$$

$$q_1' = q_1 + q_2 = \text{prob } (C_1 \text{ and } C_2 \text{ both replaced})$$

$$= q_1 + f_{2/1} \cdot \overbrace{f_1 + f_2(1-f_1)}^{q_2} - q_{2/1} \cdot q_1$$

1.2 $q_8(\text{adj}) = q_{8/7} \cdot f_7 + q_8(1-f_7)$

1.3 C_6 is not replaced only if all 3 of this type do not fail, i.e. with probability $(1-f_6)^3$. Hence $q_6(\text{adj}) = 1 - (1-f_6)^3$



Component/Assembly CA
C1'
C1
C2
C3
C4
C5
C6
C6
C6
C7
C8
C9
C9
C9
I
II
III
IV
V
VI
VII
VIII
IX
Next Higher Assembly

FIGURE 2.1

2. Find CA reliability R_{CA} and CA retainability S_{CA}

Define $R_i = (1-f_i) =$ Prob (CA has not failed in subcomponent C_i)

$S_i =$ prob (CA can be retained in NHA considering C_i **alone**)

Now for series segments of a block diagram

$$R_{CA} = \pi R_i \text{ , } S_{CA} = \pi S_i$$

And for parallel portions

$$R_{CA} = 1 - \pi(1-R_i) \qquad S_{CA} = 1 - \pi(1-S_i)$$

The 'component' contributions to retainability are easily determined:

$$S_{1'} = 1 - q_{1'} \text{ ; } S_3 = 1-q_3 \text{ ; } S_4 = 1-q_4 \text{ ; } S_5 = 1-q_5$$

(By definition and constraint A i))

$$S_6 = 1 - q_6(\text{adj}) = (1-f_6)^3$$

$S_7 = 1 - q_7 \cdot 1/2$ (from A ii), CA is replaced with prob $1/2 \cdot q_7$)

$$S_8 = 1 - q_8(\text{adj})$$

$S_9(\text{VIII}) = (1-q_9^2)$; (Section VIII assembly needs to be replaced only if both C_q's fail and have to be replaced)

$S_q(\text{IX}) = 1$; (no matter what happens in Section IV, CA can be retained)

From diagram, using series-parallel formulas, one obtains

$$S_{CA} = S_{1'} \cdot S_3 \cdot [1 - (1-S_4)(1-S_5)] \cdot S_6 \cdot S_7 \cdot S_8 \cdot S_9(\text{VIII})$$

= probability CA is retained in NHA.

3. Determine replacement rate for CA for all applications in NHA of this type.

Using (2.2) and (2.3) and constraint B,

$$\lambda_T = M(r_3' + (-\ln S_{CA})) \qquad (2.4)$$

4. To continue the inductive process on a block diagram of various CA's in the NHA, determine probabilities with this CA considered as a component

$$f_{CA} = 1 - R_{CA},\ q_{CA} = 1 - S_{CA}$$

2.4 Problems and Issues

Although the retainability procedure for obtaining probabilities and rates by working upwards from parts, components, assemblies, subsystems, system/end item is structured, one must cater the analysis to each system and its environment. One encounters problems different from those posed by the family rate - empirical replacement data approach.

1. Handbooks, models, judgement and block analyses are needed to obtain failure rates and environmental adjustment factors. Handbook data and models are sketchy for mechanical parts. To the degree that retainability estimates are dependent on reliability estimates, if the latter are poor, the former shall be.

2. For the analysis, failure rates are considered constant with time. If the rates are truly not constant, a decision is needed on where in the block analyses adjustments for time dependencies should be made.

3. Equipment specialists/provisioners are usually not trained for this type of analysis. Reliability and maintenance engineering personnel should cooperate in obtaining the retainabilities.

4. The complex analysis is not practical if done manually, especially on larger systems where the procedure is particularly attractive. Except for special cases and constraints, it is feasible to computerize most of the procedure, as are many reliability analyses of complex systems. For such a computerized procedure, the input requirements would be:

a. Failure rates by part for the provisioning environment.

b. Coding of block diagram of assemblies at various indenture levels.

c. Maintenance constraints on a component with respect to its next higher assembly.

d. Probabilities of erroneous removals (faulty diagnosis) and other interactions among components.

CHAPTER III

INITIAL ESTIMATES BY THE FAMILY CONCEPT

3.1 Basic Methodology

Conceptually the family estimator is simple. Families of similar parts are formed and statistical averages are used as estimates. Although maintenance factor values generally differ by part application, it is not usually feasible to have families of part applications, particularly on a next higher assembly (NHA) basis; it may be desirable and possible to distinguish part replacement rates by end item categories. A rate for a new part is estimated by some central tendency measure (arithmetic mean, geometric mean, median) of part's family distribution of values. It is important that the family distribution is dynamically changing - that rates on old parts be updated. This updating methodology for individual parts is discussed in Chapter IV; the revision of the master or family rate is outlined in Section 3.3.

It is reasonable to combine the family estimate as presented here with a technical estimate (e.g. as described in Chapter II). For a new part in a new provisioning situation; this topic is discussed in Section 4.4.3.

Note that the concept of using reliability replacement data from similar older systems is but a special case of the family concept, where each family has but one (or few) item - that of the older similar part or same part in a similar system.

The basic rate variable to use (see Section 4.1) is the maintenance factor per some unit usage, divided by the number of instances of that part in the end item. This rate r is the replacements/parts per unit usage. It is unlikely that families of parts can be combined across Commodity Commands, i.e. each Command would have to retain its own group of families, since a part replacement rate per 100 flying hours may differ from the part's replacement rate per 100 truck miles, for example. However, a reasonable weighted rate can be obtained for a part occurring in two different aircraft with two different values of number of applications (see Section 3.3.d).

3.2 The Navy System

Reference [1] outlines the 3M aviation usage rate system which can calculate and update a replacement rate for parts and by the aircraft (A/C) in which they are installed. Reference [2] outlines the procedure for obtaining rates r by parts (actually by FIINs of interchangeable parts) aggregated by 4 A/C categories.

$$r(i,\ell) = \text{rate for part } i\text{, A/C category } \ell$$

$$= \frac{\Sigma \text{ replacements for part } i \text{ installed in A/C in category } \ell}{\Sigma \text{ maintenance cycles for A/C in category } \ell} \tag{3.1}$$

where maintenance cycle = 100 flying hours. These rates are grouped into families (by nomenclature). Study [3] showed the best grouping method (utilizing full item name and all four positions of the FSC) generated about 20000 families for aviation materiel. Decision criteria were: number of families, number of families with one item, number of families with low standard deviation (.01, .05) and number of families with very low mean rates (.000X,.0000X). A family's distribution of values included both experienced rates and technical estimates; there was a problem with technical estimates clustering around popular guesstimates such as .01.

The "central" measure chosen was the 75th percentile since it "produced family rates which were smaller than those presently being assigned by provisioners yet large enough to provide a relatively high degree of protection to new items" [3]. Individual rates are updated yearly using exponential smoothing with smoothing parameter $\alpha = .4$.

No pilot tests were made before implementing the procedure. It is currently available only for ASO aviation materiel. No formal statistics have been gathered on the accuracy of the initial family rate versus the experienced rate since the latter (after exponential smoothing) is overlayed onto the file. The use of this estimating procedure has reduced

initial procurement of new items without affecting fleet support. There are indications that family medians (and therefore 75th percentile) still overpredict.

3.3 Recommendations for an Army System of Family Rates

a. Types of Families

Each Commodity Command would formulate and maintain families of weapon system oriented parts. A family should consist of parts that have application in end items with the same usage variable (flying hours, rounds, miles). Families should probably be distinct for consumables and reparables. Commodity oriented consumables should be formed into families (by nomenclature and FSC) and maintained by the commodity integrated materiel manager (CIMM) at TACOM and DSA/GSA. For these parts, replacement rates would not be per end item usage variables.

b. Updating Individual Rates

The individual part rates in a family should be updated per the methodology in Section 4.2.1 and 4.4.1. No major overhauling of data systems at the Commands should be undertaken. At most Commands, aggregate demand data can be used in place of consumption data to yield estimates of replacements over an extended period length (e.g. one year). The methodology of 4.2.1 is used to factor the demand. At AVSCOM, the RAMMIT system is quite adequate for providing actual replacement data on parts by end item. For all weapon system oriented parts, end item density and usage information is needed.

c. Use of the Geometric Mean

In any test of family estimates (see Chapter V), the geometric mean should be considered as a central tendency measure. For n parts with rates r_i, the geometric mean is given by

$$r_{gm} = \left(\prod^{n} r_i\right)^{1/n} \quad (3.2)$$

In [5] the authors give strong arguments for using the geometric mean as a location statistic for rate random variables, e.g., failures/hour, MTBF (hr/failure), maintenance actions/failure, demands/flying hours. Some

of the reasons:

i) Rate variable R is bounded below by zero and unbounded above. A log normal distribution often gives a good fit to empirical data; the geometric mean is the mean, median and mode of the distribution of the statistic $\Sigma \log R_i$

ii) The geometric mean is less sensitive to high values than is the arithmetic mean.

iii) The sample geometric means of R and 1/R are inversely related. The arithmetic mean does not have this property. The property becomes important if one is interested in ratios of failure rates λ or MTBF's under different environmental conditions, i.e.

$$\frac{\text{g.m.}(\lambda_1)}{\text{g.m.}(\lambda_2)} = \frac{\text{g.m.}[1/(\text{MTBF})_1}{\text{g.m.}[1/(\text{MTBF})_2} = \frac{1/\text{g.m.}(\text{MTBF})_1}{1/\text{g.m.}(\text{MTBF})_2}$$

Therefore a conversion factor f for λ ratios = 1/f' where f' is a conversion factor for MTBF's.

d. Weighted Rate for a Part

I introduce the concept by example.

Let part P_1 occur in end item ε_a, ν_a times

Let part P_1 occur in end item ε_b, ν_b times

The number of replacements per end item a (b) per unit usage is given by $R_a (R_b)$. Then the weighted rate per part 1 to be stored in the family file is*

$$r_1 = \frac{R_a}{\nu_a} w_a + \frac{R_b}{\nu_b} w_b \quad \text{where } w_a = \frac{\nu_a}{\nu_a+\nu_b} \quad w_b = 1-w_a$$

e. Role of Technical Estimates

Technical estimates should not be included in a family of values. The initial estimated rate for a new part should be a combination of the latest "central" value of the dynamic family distribution and the engineer's

* Note for these weights, stored rate is equivalent to $(R_a+R_b)/\nu_a+\nu_b)$

best estimate under actual field conditions. See Section 4.4.3.

3.4 Problems and Issues

a. Standard nomenclatures for parts must be established, e.g. CAPAC'T'R or C'P'CITOR?

b. Families have to be formed. Various ways of grouping have to be investigated to form "homogeneous" families that are not too large or too small. Groups of families have to be obtained for different materiel, e.g. aviation, electronic, tank-automotive.

c. The concept should be tested - probably on aviation materiel using the RAMMIT system at AVSCOM. The test should determine how accurate family estimated rates are compared to provisioning master data record (PMDR) maintenance factors in predicting actual replacements. The test should determine how necessary is the part application distinction (by NHA) since the family technique cannot easily maintain this distinction. The initial cost of provisioning indicated by the various estimates should be determined.

Unfortunately there is a catch-22 involved in testing. There is no updating currently of the PMDR maintenance factors; hence, these MF's do not reflect past or present consumption data. If we form families of "bad" rates from the PMDR values and then compare family estimates with observed replacements on recently fielded end item, we may very well reject the family procedure. Ergo no updating system would be instituted.

d. Problems arise if MF or replacement rates are truly very non-linear with usage. A rate variable expressed per some unit of end item usage presupposes that some percentage increase in usage generates an identical percentage increase in replacements.

Also there is evidence [4] that the maintenance factors for parts on a truck are odometer and/or age dependent. Therefore, the replacement rates for older parts in a family may increase the central measure such that its value does not adequately reflect the initial replacements rate of a new part.

CHAPTER IV

UPDATING MAINTENANCE FACTOR AND DEMAND ESTIMATES

4.1 Introduction

In this chapter we are concerned with obtaining reasonable methods of updating initial estimates of demand, maintenance factor, and the related variable, replacement rate; using available observations, over a period of time, of demand and/or replacements. First we define some generic variables and make distinctions amongst the things we are updating. For some period of time:

D_i = demand for the part in end item i upon a certain support level

MF_i = number of replacements of part/end item i per some unit usage = maintenance factor*

U_i = usage (flying hours, miles, rounds) associated with end item i

ρ_i = density of end item i

ν_i = number of instances of part in one end item i

r_i = number replacements/part per some unit usage = replacement rate*

R_i = number of replacements of part on end item i

Capped variables $\hat{D}$, $\widehat{MF}$, $\hat{r}$ denote estimates.

D and R are clearly not equivalent. Clearly also estimates $\widehat{MF}$, $\hat{r}$ should be updated using observations on R, and $\hat{D}$ should be updated using observations of D at that support level. Generally consumption data (R) is not available and one must therefore manipulate demand data. Moreover if only aggregate demand data at some high support level is available, one has often lost distinction of end item type, among other things.

For the rest of the chapter, we concern ourselves with demand at the wholesale level. The maintenance factor, suitably adjusted, is then a reasonable initial estimate of demand since total replacements are eventually seen as demands upon this level. For lower level initial demand estimates the MF has to be suitably factored by the replacement task distribution [7]. An initial estimate of demand for period 1 is given by:

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*Distinction between MF_i and r_i will be clarified.

$$\hat{D}_i(1) = \widehat{MF}_i \cdot \rho_i(1) \cdot U_i(1) \tag{4.1}$$

where $\rho_i(1)$, $U_i(1)$ are density and usage projections for period 1. Subsequently as demands $D_i(1)$, $D_i(2)$, etc. one observed one can update (4.1) via

$$\hat{D}_i(n+1) = [1 - G(n)] \cdot \hat{D}_i(n) + G(n)\, D_i(n) \tag{4.2}$$

where 1-G,G are variable weights assigned to the previous estimate and the current demand.

From definitions, one can see that

$$\frac{MF_i \cdot \rho_i}{\nu_i \cdot \rho_i} = r_i = \frac{R_i}{\nu_i \cdot \rho_i \cdot U_i} \tag{4.3}$$

r_i is a more basic variable related to the part that is more useful for storing as a "family" variable than MF_i, which depends upon ν_i; that is, a part could have one replacement rate r and two maintenance factors MF_1 and MF_2 for two types of end items with $\nu_1 \neq \nu_2$.

Nevertheless, assume for the moment we were to store and update maintenance factors. If, after a period of time, I, we can observe the number of replacements in the field for the part in end item i, the environmental conditions, and the end item usage and density, what would be our updated estimates $\widehat{MF}$ and $\hat{R}$? We would first adjust our initial MF for the actual environmental conditions, $\widehat{MF}_i(I)$. Then using (4.3)

$$\widehat{MF}_i(II) = [1 - H(I)]\, \widehat{MF}_i(I) + H(I)\, \frac{R_i(I)}{\rho_i(I)\, U_i(I)} \tag{4.4*}$$

(We use Roman numerals to distinguish periods here from periods used in (4.1), (4.2), and (4.5); for example $\hat{R}$, $\hat{D}$ estimates may be updated quarterly but $\widehat{MF}$ only yearly.)

---

* In equations 4.4 - 4.16, H, L, J are weighting factors.

On the other hand

$$\hat{R}_i(2) = [1 - L(1)]\, MF_i(1) \cdot \rho_i(2)\, U_i(2) + L(1)\, R_i(1) \qquad (4.5)$$

If demand data has to be used by necessity to replace replacement data, algorithms (4.4) and (4.2) do not differ conceptually. For completeness, a replacement rate update is given by

$$\hat{r}_i(II) = [1 - J(I)]\, \hat{r}_i(I) + J(I) \cdot \frac{R_i(I)}{\rho_i(I) U_i(I) \nu_i} \qquad (4.6)$$

Finally a basic question arises: of what use is a stored, updated MF when one is concerned with initial support of a new system in a different environment?

To focus the previous discussion, there are three problems we wish to consider further:

1. How to break out realistic sources of data (aggregate demand data at depot or wholesale level) to obtain observables with which to update MF estimates and particular demand estimates.

2. How to weight a demand estimate using maintenance factors with a demand estimate using demand experience.

3. How to modify the formulas for updating maintenance factors, replacement rates:

   i) using a family estimate in lieu of individual ones.

   ii) combining a stored rate (family or otherwise) with a new technical estimate (e.g. reliability, retainability analysis of parts in a new system and new environment).

4.2 Updating Estimates Using Aggregate Demand Data

4.2.1 Intensity Factors

Suppose we have an imperfect data base to some degree, i.e., we have demand data (not replacements) at some support level and it is aggregated in some manner - we have lost part application distinction

and/or end item identification and/or deployment area. Suppose we have end item density and usage information (the approach doesn't require this, but gives better breakouts by allowing density and usage adjustments to maintenance factors).

Add to definitions in Section 4.1:

D = observed aggregate demand

$D_\varepsilon(\cdot)$ = an expected demand based on MF's or r's

Let us consider a consumable part, common on two different end items

Using MF's, we factor out D as follows:

$$D \cdot \frac{MF_i \cdot \rho_i \cdot U_i}{MF_1 \cdot \rho_1 \cdot U_1 + MF_2 \cdot \rho_2 \cdot U_2} = D_i \ , \ i = 1,2 \qquad (4.7)$$

or

$$D_i = D \cdot I_i \quad \text{where } I_i = \text{Intensity Factor} \qquad (4.8)$$

This factored demand D_i for period n can be used in algorithm (4.2) for updating demand estimates for part in end item i.

Equation (4.7) is especially interesting when we consider that $D_i/\rho_i U_i$ is a current observed "MF_i" related to old MF_i by

$$\frac{D_i}{\rho_i U_i} = MF_i \ \frac{D}{MF_1 \cdot \rho_1 \cdot U_1 + MF_2 \ \rho_2 \cdot U_2} \qquad (4.9)$$

The denominator of (4.9) is an expected value of demand $D_\varepsilon(MF)$. Therefore

$$\hat{MF}_i(\text{current}) = \hat{MF}_i(\text{old}) \cdot \left[\frac{D}{D_\varepsilon(MF)}\right] \qquad (4.10)$$

(4.10) indicates that we obtain a current MF observation by adjusting the old MF by the ratio of actual to expected aggregate demand. Finally we utilize (4.4) to update:

$$\hat{MF}_i(\text{new}) = (1 - H)\ \hat{MF}_i(\text{old}) + H \cdot \hat{MF}_i(\text{current}) \qquad (4.11)$$

Similarly using replacement rates r, we factor out D as follows:

$$D \cdot \frac{r_i \cdot \nu_i \cdot \rho_i \cdot U_i}{r_1 \cdot \nu_1 \cdot \rho_1 \cdot U_1 + r_2 \cdot \nu_2 \cdot \rho_2 \cdot U_2} = D_i \text{ , } i = 1,2 \qquad (4.12)$$

$$D_i = D \cdot I_i = (r_i \nu_i \rho_i U_i) \cdot \frac{D}{D_\varepsilon(r)} \qquad (4.13)$$

Second form of (4.13) leads directly to (from 4.6)

$$\hat{r}_i(\text{new}) = (1-J)\ \hat{r}_i(\text{old}) + J \cdot \hat{r}_i(\text{old}) \ \frac{D}{D_\varepsilon(r)} \qquad (4.14)$$

Note that if one assumes $MF_i \propto \nu_i$ and $r_1 = r_2$, then intensity factors in (4.7) + (4.12) are identical.

One can see from the simple example that intensity factors break out any aggregate demand or consumption data in a reasonable manner on a function of the MF's (if density and usage is unavailable, simply use $\left(\frac{MF_i}{MF_1+MF_2}\right)$. In a working dynamic data system these intensity factors would change as the MF's themselves are updated. By using adjusted MF's (or rates r), the intensity factor automatically prorates the visible demand at a higher echelon for differences in density, usage, environment, multiple applications.

The use of the ratio $D/D_\varepsilon(\cdot)$ is quite simple also in updating MF's and replacement rates r.

Note also that end items 1 and 2 need not have the same usage variable; as long as the terms $MF \cdot \rho \cdot U$ are dimensionally consistent, U_1 may be flying hours and U_2 truck miles.

4.2.2 Coefficients of Regression

In terms of the simple example in the previous section, suppose over a substantial number of periods, one had enough observations on D, ρ_1, U_1, ρ_2, U_2 to form a regression equation on the variables $(\rho_i U_i)$

$$D = \beta_1 \cdot (\rho_1 U_1) + \beta_2 \cdot (\rho_2 U_2) \qquad (4.15)$$

Then for given future set of usage, densities (ρ_1^*, U_1^*, ρ_2^*, U_2^*) one could form intensity factors

$$I_1^* = \frac{\beta_1 \rho_1^* U_1^*}{\beta_1 \rho_1^* U_1^* + \beta_2 \rho_2^* U_2^*} \qquad (4.16)$$

This method requires many observations but once reliable β's are found, the proper prorating using (4.16) is readily determined.

4.2.3 Problems and Issues

For reparable items, one has to be careful in inferring replacements and maintenance factors from visible demand data at a high echelon. Is higher demand due to increased failures-replacements, increased washout rate, or a higher percentage of items being sent to that echelon? For example

Initial Estimates

		ORG	DSU	GSU	DEPOT
MF = 100	MTD:	50	20	10	$\underbrace{\text{10 repaired 10 washout}}_{\text{visible 20 expected}}$

Actual Data

40 demands at depot

	ORG	DSU	GSU	DEPOT
Imply MF = 200:	100	40	20	40
or MF = 120:	50	20	10	40

or some other mix

For present purposes we will assume that washout and maintenance task distribution percentages are correct, so that implied MF = 200.**

Another source of error in the analyses of the preceding sections is that MF is generally non-linear in usage or other environmental factors. Some of these non-linearities can be smoothed out by adjusting the MF estimate from period to period (see [4]).

** Incipient development by IRO indicates a reasonable procedure for relating percentage changes in parameters (MF, washout rate, MTD, etc) to percentage changes in observable demand.

There are two major alternatives for a data base - a perfectly visible system from the field up, or visibility on demands at some high echelon plus usage, density information. I see little payoff in gradations between these two - once one loses partial visibility on environmental conditions, processing errors, actual task distributions, and given the volatility of the data, one is not much worse using depot or wholesale data as using an intermediate level.

The RAMMIT system at AVSCOM is a highly visible system on maintenace actions at various levels on parts in aviation systems. With part replacement actions and past density and usage information by end items, one can do a post hoc analysis on how well intensity factoring of aggregate data would have done in projecting subsequent replacements by end item or deployment area.

4.3 Relative Weighting of Demand Experience and Maintenance Factors

It has been found [ℓ] in forecasting demand that it is best to obtain estimates of a demand per total period usage; this rate x is then multiplied by projected period usage in future periods. In the notation of Section 4.1, dropping the subscript i which is not needed here

$$\hat{x}(n) = \widehat{\left(\frac{D(n)}{\rho(n) \cdot U(n)}\right)} = \text{estimate after period n} \qquad (4.17)$$

where $\rho(n) \cdot U(n) \equiv H(n)$ = total usage (e.g. flying hours) for the end item population in period n

Let $y(n)$ = actual demand per usage in period n

$\hat{\mu}(n)$ = maintenance factor per usage estimate in period n, which in general based on Gotwals work [+], can vary by period.

Orr finds [ℓ] that $\hat{x}(n)$ should be updated using actual demand per usage experience as follows:

$$\hat{x}(n) = (1 - G(n))\, \hat{x}(n-1) + G(n) \cdot y(n) \qquad (4.18)$$

with $$G(n) = \frac{1 + k\,G(n-1)}{1 + k\,G(n-1) + k\,H^2(n-1)/H^2(n)} \qquad (4.19)$$

where k = a forecast parameter dependent on yearly frequency of demand

Orr [9] develops rational weights in the combined estimate in (4.20)

$$X(n) = (1 - \mathcal{A}(n)\hat{\mu}(n) + \mathcal{A}(n)\hat{x}(n) \qquad (4.20)$$

where

$$\mathcal{A}(n) = \frac{\tau^2(n)}{\tau^2(n) + \gamma^2(n)\,G(n)} \qquad (4.21)$$

$\tau^2(n)$ = variance of estimate $\hat{\mu}(n)$

$\gamma^2(n)$ = variance of observed $y(n)$;
it is proportional to $1/H^2(n)$

$\gamma^2(n)G(n)$ = variance of estimate $x(n)$

and with $G(n)$ varying as in (4.19) with $G(1) = 1$

If usage $H(n)$ increases uniformly over two years of initial deployment and $\mu(n)$ increases with the square root of average odometer readings [4], then the typical weighting curve $(1 - \mathcal{A}(n))$, plotted for 3 months periods, is shown in figure 4.1. Plotted also is the current weighting curve recommended by DoDI 4140.42. Initially more weight is given to the "maintenance factor" estimate than currently recommended; in the second year of the phase-in of the end item of the part, more weight is given to observed experience than does the DoDI curve.

4.4 Modifications of Formulae for Updating Maintenance Factors

4.4.1 Modified Algorithm

Equations (4.4) or (4.6) or (4.11) or (4.14) could be used to update on, say, a yearly basis. However, another algorithm is more appropriate for estimating maintenance factor or rate variables which, when discounting usage and density variations by period, are relatively

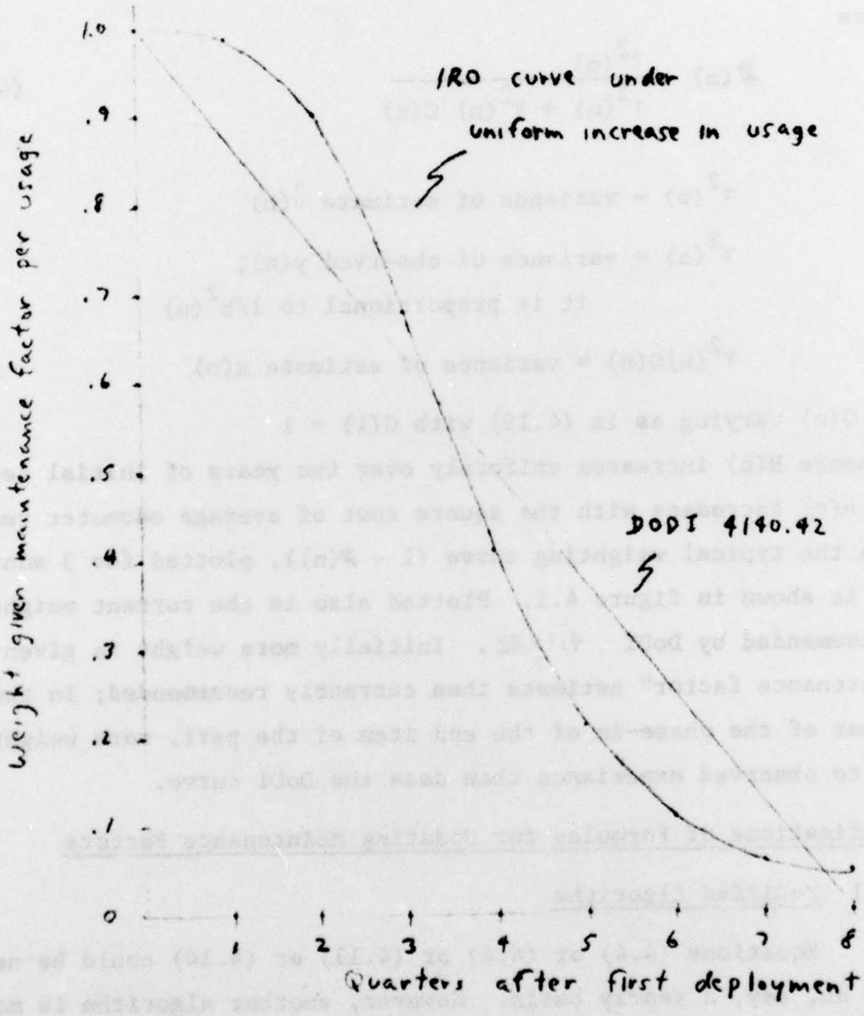

Figure 4.1 Weighting Curve for Initial Estimates

I shall discuss the algorithm in terms of the replacement rate r.

Let

$$W_k(I) = \frac{R_k(I)}{\rho_k(I)\ U_k(I)\ \nu_k} \tag{4.22}$$

where k is an index for what deployment area, for what type of end item, the replacements (or demand) $R_k(I)$ are given in year I.*

$\hat{r}(o)$ = initial estimate of replacement rate

$n(I)$ = number of $W_k(I)$ observations in year (I)

Then an update for r after year I [7],

$$\hat{r}(I) = \frac{1}{n(I)\ A + 1}\ \hat{r}(o) + \frac{n(I)A}{n(I)\ A + 1}\ \overline{W}(I) \tag{4.23}$$

where

$$\overline{W}(I) = \frac{1}{n(I)} \sum_k W_k(I) = \text{sample mean} \tag{4.24}$$

$$A = \frac{\text{Variance}\ (\hat{r}(o))}{\text{Variance}\ (W_k)} \text{ or } \frac{\text{VMR}(\hat{r}(o))}{\text{VMR}(W_k)} \tag{4.25}$$

After year II, we have n(II) more observations and

$$\hat{r}(II) = \frac{1}{(n(I) + n(II))A+1}\ \hat{r}(o) + \frac{(n(I) + n(II))A}{(\qquad)A + 1}\ \overline{W}(II) \tag{4.26}$$

$$\text{where } \overline{W}(II) = \frac{1}{n(I) + n(II)} \sum_k W_k(I) \tag{4.27}$$

$$= \text{sample mean after 2 years.}$$

As more observations are gathered more weight is put on $\overline{W}(\cdot)$.

In determining A, one can find the variance and VMR of W_k statistically from observations or by assuming a distribution (a log normal is often good for a rate variable); uncertainty in the initial estimate determines

---

*W_k may be obtainable only from the method culminating in (4.10).

variance and VMR* of $\hat{r}(o)$. If the prior estimate is good, A is small, and more weight is initially put on $\hat{r}(o)$.

Maintenance factor per usage estimates can be obtained from $\hat{r}$ by multiplying by ν_k, the number of part applications associated with index k.

4.4.2 <u>Use of Family Estimates</u>

If one has the distribution of the family rates to which the part belongs, one immediately has the variance $(\hat{r}(o)$ and VMR$(\hat{r}(o))$ in terms of these catalog parameters. Also from [10], there are theoretical reasons why the variance (W_k) in a relatively homogeneous family would be of the form

$$\text{Var}\ (W_k) = B_1 E(W_k) + B_2 (E(W_k))^2 \tag{4.28}$$

It must be remembered that the family distribution is dynamically changing, since new updated rates on old items are being stored, thereby changing the catalog parameters (e.g. mean and variance). Also, as pointed out in Chapter 3, one need not necessarily use the catalog arithmetic mean as an initial r(o); a median or geometric mean or other central tendency measure may be desirable.

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*Variance to Mean Ratio

4.4.3 Combining a Stored Estimate With a New Technical Estimate

There should be some (some say most) weight given to an independent engineering estimate (e.g. as obtained from retainability analysis) of the replacement rate on a part in its new milieu - new system, new physical conditions, new maintenance support environment. The stored replacement rate is a statistical estimate for past conditions, albeit perhaps for similar situations.

Although I do not believe a family file of rates should be contaminated with technical estimates (unless perhaps the file would be nearly empty otherwise), the $\hat{r}(o)$ for a part should be a combination of a family central measure and a technical estimate. After year I, the r(I) will be stored in the family file and will, in part, reflect the original technical estimate.

The natural weighted combination for minimum variance estimators is:

$$\hat{r}(o) = \left[\frac{\text{Var } r_T}{\text{Var } r_T + \text{Var } r_f}\right] r_f + \left[\frac{\text{Var } r_f}{\text{Var } r_T + \text{Var } r_f}\right] r_T \qquad (4.29)$$

where

r_f = family estimated replacement rate

r_T = technical estimated replacement rate

CHAPTER V

RECOMMENDATIONS

In this chapter I briefly outline some recommended courses of action on the aspects of maintenance factor methodology discussed in this report. Initial action documents will typically be letters to the sponsor with reference to this report or with appendices of technical details.

a. Retainability analysis for initial estimates of maintenance factors.

It is recommended that the DARCOM sponsor send this report under cover letter to at least two subordinate Commands to review the appropriate sections. IRO envisions the retainability technique as an ad hoc tool applied to specific systems.

b. Curve of weights applied to the maintenance factor estimate of demand (versus experienced demand) over initial eight quarters of deployment.

IRO shall postulate several $\setminus$ - type curves represented in Figure 4.1 and detail procedures for generating them for current and future forecasting schemes. These are expected to be viable alternatives to the $\setminus$ - type curve of DoDI 4140.42.

c. Updating the MF

IRO shall be responding to system change request SCR # CARNEE 614501 in Jan 1977. Pillars of the method will be the intensity factor equations (4.7)-(4.10) and equation (4.11).

d. Modifications for updating MF or replacement rates.

The use of family rates combined with technical estimates, the updating procedure, and ways of forming families and analyzing their statistical properties - all these procedures can best be analyzed and tested on aviation materiel under the RAMMIT data processing system at AVSCOM. After discussion with RAMMIT peronnel, IRO shall draft some proposals for experimentation.

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